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DEVELOPMENT OF RESEARCH ON THE CREATION OF CYBERNETIC ACCELERATORS

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THE fundamental principle of phase stability of particles in resonant cyclic accelerators, discovered by V. I. Veksler, has eliminated the energy limitation inherent in classical cyclotrons, and made it possible by the same token to overcome, so to speak, the "relativistic barrier." But a new barrier in accelerator construction—the "economic barrier"—has arisen with further increase in the proton energy, above 10 GeV in weak-focusing proton synchrotrons, which inevitably have appreciable magnetic-gap aperture cross sections and consequently an electromagnet of large weight and large power drain.

The strong-focusing principle proposed by Christofilos, Snyder, Livingston, and Courant greatly improved the situation and made it possible to reduce considerably the dimensions and the power supply of the electromagnet. Thus, for example, the electromagnet of the CERN proton synchrotron weighs 4000 tons at a maximum particle energy 30 GeV, whereas the electromagnet of the bevatron, designed for a proton energy 6.2 GeV, weighs 10000 tons, that is, a strong-focusing accelerator with five times the particle energy has an electromagnet whose weight is smaller by a factor 2.5 than in the case of a weak-focusing accelerator; we see that the ratio in favor of the strong-focusing system is approximately twelve.

The construction of the Serpukhov machine, designed to accelerate protons to 70 GeV, is now nearing completion. This strong-focusing accelerator is the largest in the world and will apparently remain for a number of years the largest installation for experiments in the field of high-energy physics.

Progress to still higher proton energies, on the order of hundreds of GeV and up to 1000 GeV, is conceivable only with the aid of the strong-focusing principle. In this case, however, the cost of the accelerators will be exceedingly high. Moreover, the unusually stringent requirements with respect to the structure of the magnetic field, and consequently the extremely difficult tolerances in the manufacture, installation, and subsequent operation of the electromagnet elements, with further attempts to decrease the aperture of the magnetic gap, lead to the appearance of a new barrier—the "barrier of technical realization," that is, to the question of the real feasibility of the design of such an accelerator and its operating stability in time.

To overcome this barrier, É. L. Burshteın, A. A. Vasil'ev, V. A. Petukhov, S. M. Rubchinskiı, and the author proposed in 1961 the principle of automatic correction of the magnetic field by means of data on the position of the accelerated-particle orbit in a vacuum chamber placed in the gap of an electromagnet. Following a preliminary communication, published in 1961, the principles of the construction of a cybernetic accelerator for energies up to 1,000 GeV were reported at the International Conference on Accelerators in Dubna (1963). Since that time, theoretical and design work has been vigorously pursued at the Radiotechnical Institute of the USSR Academy of Sciences towards creation of a 1000-GeV proton accelerator and its 1-GeV model. A major part in the development of the design was assumed also by the scientists of the Moscow Engineering-physics Institute and of the Joint Institutes for Nuclear Research.

These design activities were preceded by serious discussions in the USSR, at a special conference in CERN (Switzerland), and in Brookhaven (USA) on the advisability of developing and constructing accelerators for ultra-high energies. All three groups (USSR, the European group (CERN), and USA) arrived at a single answer: the creation of proton accelerators for energies up to 1000 GeV at intensities 10^{13}–10^{14} particles in each pulse is desirable and necessary.

As a result of initial investigations, we considered the following variants for the further development of 1,000-GeV accelerators with automatic correction of the magnetic field:

1) A two-step system with a 200-MeV linear proton accelerator-injector and a large ring system, in which the particle energy increases from 200 MeV to 1000 GeV.

2) A two-step system with a 1-GeV linear proton accelerator-injector and a large ring system raising the energy of the particles to 1000 GeV.

3) A three-step system with a 200-MeV linear proton accelerator-injector, an intermediate ring accelerator booster raising the particle energy to 6 GeV, and a large ring system in which the particle energy is raised from 6 to 1000 GeV.

In all three variants, we assured a maximum magnetic-field intensity 13 kOe in the electromagnet gap an orbit radius of curvature of 2570 meters, and a vacuum-chamber cross section from 6 to 20 cm^2. Further analysis of this question, carried out during the time of the preliminary design of the 1000-GeV cybernetic accelerator at the Radio Engineering Institute of the USSR Academy of Sciences, and also investigations of the magnetic blocks of the 1-GeV model of this accelerator, have demonstrated the feasibility of increasing the magnetic field intensity in the electromagnet gap to 16 kOe. This circumstance made possible, for a rated energy 1000 GeV, to decrease somewhat the radius of curvature of the orbit, to 2,080 meters, and also to lower the length of the orbit from 20.0 to 15.55 km.

An analysis has shown that the injection energy should be increased to 18 GeV. This value determines the output parameters of the ring accelerator-booster.

The vacuum chamber in the gap of the large electromagnet will have an elliptic cross section at a chamber height 40 mm and a radial length 60 mm, that is, 26.0 cm^2.

The energy increment per revolution in the large ring is 56 MeV.

The frequency modulation of the accelerating voltage is 0.12% (this can be attained in a relatively simple manner).

The acceleration time is one second at 20 acceleration cycles per minute.

The total power consumed by the accelerating system is 23 MW.

The phase stability requirement in ring-type proton accelerators, in accordance with the theory of V. I. Veksler, leads to the necessity of simultaneously varying the intensity of the magnetic field and the frequency of the accelerating voltage in accordance with a specified program, which follows from the fact that with increasing energy, and consequently, particle mass, the radius of the orbit should remain unchanged. Failure to satisfy this requirement causes the particles to land on the walls of the vacuum chamber and to drop out of the acceleration process. The larger the radius of the particle-beam orbit and the smaller the dimensions determining the cross section of the vacuum chamber or, what is the same, the aperture of the electromagnet gap, the more difficult it is to satisfy this requirement. The system provided in the accelerator for automatically regulating the position of the orbit is intended to ensure correction of the magnetic field of the accelerator in order to ensure dependably the passage of the particle beam near the axis of the vacuum chamber. The operating principle of the system consists in using signals from pickups that measure the transverse coordinates of the beam together with information concerning the state of the magnetic field to correct the field.

An important role is played in the cybernetic accelerator by the choice of the method of compensation for the distortion of the magnetic-field configuration. To this end, a system of correcting lenses (quadrupole and sextupole) is provided. Two stages of regulation of the orbit displacement are provided: transverse deviation of the particle beam during the period of the injection, and transverse deviations of the instantaneous equilibrium orbit during the acceleration period. The automatic control system for the orbit position contains 264 beam-deflection pickups, 528 correcting devices with amplifiers feeding their windings, and a computing device which determines the necessary values of the currents in the windings of the correcting magnets and lenses with account taken of the beam-pickup signals.

The high reliability of the orbit control system is ensured by automatically switching off faulty elements and simultaneous action of the properly operating elements, the number of which was chosen with due allowance for the provision of spare elements.

Any deviation in the decrement of the magnetic field in the electromagnet blocks leads to a change in the frequency of the betatron oscillations and to the appearance of resonance excitations of the beam, causing the need for stringent tolerances for the field-decrease coefficient. By correcting the gradient of the magnetic field in accordance with the information obtained on the motion of the beam of the accelerated particles it is possible to relax these tolerances appreciably.

The operating principle of the control system for the betatron-oscillation frequency consists in the following: The accelerated-particle bunches are made to execute betatron oscillations by means of a special exciter. Signal electrodes are installed at a distance from the exciter equal to an integer number of half-waves of the betatron oscillations plus one-quarter wavelength. The electrode voltage is proportional to the displacement of the center of gravity of the particle bunch. A certain spectral component from the voltage produced on the signal electrodes is separated. The frequency of this component is compared with the value it should have in accordance with the design. The error signal controls the current in the quadrupole lenses, which correct the gradient of the accelerator control field. The disturbance that excites the betatron oscillations of the center of gravity of the particle bunch should be such that, on the one hand, these oscillations exist at the instants when the frequency is measured during the entire time of the acceleration, and on the other hand the transverse dimensions of the beam at the end of the cycle of the acceleration not exceed the transverse dimension of the cross section of the vacuum chamber of the accelerator.

The spatial harmonics of the gradient are regulated by using information obtained as a result of separating and processing the harmonics of the betatron oscillations of the beam, corresponding to parametric excitation, for compensation of the spatial harmonics with frequencies $2Q$ and $2Q \pm 1$, where Q is the number of the betatron oscillations.

We wish to add that a 1-GeV model of the cybernetic accelerator was constructed at the Radio Engineering Institute, and it is planned to use it for an experimental investigation at the joint operation of the automatic-control systems for the accelerator parameters on the basis of the beam information; these systems will then be used in the large accelerator.

The 1-GeV accelerator can in itself serve as a prototype of a small accelerator for research purposes. This model incorporates, for the first time, automatic control of the position of the orbit of the accelerated particles, making it possible to decrease the aperture of the vacuum chamber and to relax the stringent requirement concerning the rigidity of the foundation of the accelerator.

The proton acceleration process consists of four stages:

1) Passing the beam at the injection-energy level through the ring chamber of the accelerator (operation of the first revolution); during this stage, the control system compensates for the inaccuracy of the construction and arrangement of the magnet blocks.

2) Single-turn injection (4 μsec).

3) Acceleration (0.4 sec); during this stage the energy of the particles increases from 1 MeV to 1.1 GeV;

4) Extraction of the accelerated particles.

By now, the preparation and erection of all the accelerator elements have been completed. The operation of the vacuum chamber and of the vacuum system has been adjusted. The operating vacuum is better than 1×10^{-6} mm Hg. At so small a cross section of the vacuum chamber, this is attained by connecting to a number of the sections of the chamber a vacuum collector with large diameter, to which are connected five systems of high-vacuum units with titanium ion-absorption pumps.

The problem of the first revolution has been solved. In addition, beam circulation (up to 20 revolutions) with very small particle loss has been attained.

The "Dnepr" digital computer, with rather modest characteristics (4000 operations per second), is used as the electronic control computer.

The elements of the electromagnet were built in the experimental machine shop of the Radio Engineering Institute with a high degree of precision. Each block of the electromagnet was measured and tested very accurately. This was done in order to organize a large program of research on a purposeful and accurately controlled variation of the positions of the electromagnets in order to reveal the actual tolerances which can still be allowed by the automatic-control system.

We present a few data on the 1-GeV model of the cybernetic accelerator:

1. The average radius of the orbit (8.5 m) is determined by the dimensions of the test room of the institute.
2. Injection energy—1 MeV. The injector is an electrostatic Van-de-Graaff generator, constructed in our own shop, operating at 1 MV.
3. Magnetic field induction at injection—250 G.
4. Same at ejection—10 kG.
5. Number of magnetic blocks—100; their windings are water cooled.
6. Length of blocks—35 cm.
7. Number of betatron oscillations per revolution—6.25.
8. Aperture of vacuum chamber 1.6×2.2 cm^2. The chamber is made of an oval tube of thin stainless steel. The gaskets between sections are made of indium.
9. Particle revolution frequency at injection—260 kHz.
10. The same at ejection—4.8 MHz.
11. Energy increment per revolution—1000 eV.
12. Radio frequency multiplicity—5.
13. Weight of iron of entire magnet—12 tons.
14. Weight of copper of magnet—4 tons.
15. Number of pairs of electrostatic electrodes—20.
16. Number of sets of correcting magnets—20.
17. Accuracy of measurement of the position of the orbit, radially and vertically—0.25 mm.
18. Number of particles injected in one-revolution injection—$(2.5 - 5) \times 10^{10}$.
19. Number of accelerating radio-frequency stations—10.

In conclusion, I wish to dwell briefly in the influence of V. I. Veksler's main ideas on the development of the idea of the cybernetic accelerator.

In the beginning of this report I already indicated that the first and most important of the three barriers encountered in the construction of cyclic proton accelerators for high and ultra high energies was the relativistic barrier. Neither the strong-focusing principle nor the automatic correction of the magnetic field can be used if the basic problem of phase stability of particles is not solved. This is the underlying basis of the construction of cyclic accelerators of the resonant type. Therefore the names of Lawrence and Veksler will always shine with undiminished brightness in the history of science. Lawrence's classical cyclotron built the foundation for the creation of the first accelerators for the study of the physics of the atomic nucleus. On the other hand, Veksler's ideas gave rise to a number of classes of cyclic accelerators for light and heavy particles and for multiply charged ions. Synchrotrons, synchrocyclotrons (called phasotrons by Veksler), microtrons, proton synchrotrons (or synchrophasotrons) with weak and strong focusing, and cybernetic accelerators—they all make up the tribe of accelerating installations that help our own and the world's science to perform fundamental research in the field of high-energy physics for the benefit of humanity, and are the result of the discovery of the phase focusing principle discovered by Veksler. This is why we all greeted with such great satisfaction the award of the international "Atoms for Peace" prize to V. I. Veksler.

I wish to devote this modest communication concerning our work to the memory of V. I. Veksler, we shall always think of his death with a feeling of deep grief, and of his famous deeds with a sense of great gratitude and pride.

Translated by J. G. Adashko